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# MECHANISMS OF STRENGTHENING AND FRACTURE IN COMPOSITE MATERIALS

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A. S. Tetelman
Associate Professor

Department of Materials Science
Stanford University
Stanford, California

## INTRODUCTION

This report describes research activities that were performed during the sixth phase of a program designed to investigate the mechanisms of strengthening and fracture of composite materials. As mentioned in the previous progress reports (subsequently referred to by PR number), five different programs are being carried out. These are discussed separately in the following paragraphs.

### I. The Effect of Drilled Holes on the Notch Toughness of Iron Base Alloys (with C. A. Rau, Graduate Student)

The effect of mechanically drilled holes on the notch toughness of iron-base alloys has been investigated by means of instrumented impact-bend, slow-bend, and tension testing. Although one small hole (diameter = 0.0292") drilled at or below the notch tip produces insignificant or adverse effects on the Charpy-V transition behavior, two holes located on each side of the notch produce considerable improvements. The important geometric parameters which determine the magnitude of the improvement were investigated. The impact transition temperature of drilled specimens can be as much as 60°C lower than that of standard Charpy samples. In addition, two holes increase the load carrying capacity of Charpy samples by as much as 100% at low temperatures where both specimens fracture completely by cleavage prior to general yielding.

A photoelastic stress analysis revealed that these improvements are obtained without markedly reducing the elastic stress concentration factor of the notch. However, metallographic examination of etch-pitted specimens of Fe-3% Si showed that two holes cause a marked redistribution of local plastic strains away from the notch tip and between the notch side and each hole. As a result, two holes reduce the rate at which the plastic stress concentration factor builds up with applied load, and thus holes increase the applied load required to produce the critical fracture stress or strain below the notch root. In addition, when ductile tearing occurs to both holes, the resulting "hammerhead" notch is so blunt that fracture reinitiation requires much higher energy. Other geometries such as increased hole size and additional number of holes were able to further improve the nominal notch strength at low temperatures, but they tended to be less effective than two 0.0292" holes at higher temperatures. Similar improvements were also obtained in Charpy type samples of reduced thickness and sheet tension samples, indicating that plane strain conditions are not a prerequisite for improvement with holes.

Although a general geometric effect, the magnitude of the improvement from hole drilling varies with microstructure. In a series of hypoeutectoid steels, holes increased the notch strength by similar amounts when failure occurred prior to general yielding. However, the reduction in the ductility transition temperature due to holes increased rapidly with the steel's carbon content in mild steels (%C $< 0.2$) and then decreased with additional carbon content. The percentage increase in the shelf energy of fully ductile samples showed no such maximum and increased continuously as the ductile tear energy decreased.

## II. Fracture Mechanisms in Quenched and Tempered Steels

(with Darel Hodgson, Graduate Student)

Deformation and fracture mechanisms have been studied in a dispersed, two-phase system. Quenched and tempered (or spheroidized) carbon steel was used as a model system. Steels with 3 to 13 volume percent of hard, spherical carbides were studied by varying the carbon content, and mean particle sizes ranging from $0.2\mu$ to $1.5\mu$ were obtained by tempering at temperatures from $500^{\circ}C$ to $700^{\circ}C$ for 24 hours.

Standard Charpy V-notch specimens, tested in slow-bend, were used to obtain conditions of severe triaxiality and stress concentration; also, standard flat tensile specimens contributed yield stress and strain hardening data. For each mean particle size and volume fraction, specimens were tested between room temperature and $-196^{\circ}C$. Curves of Charpy general yield load, fracture load and bend angle as a function of temperature were obtained for each steel condition. From these curves, the nil ductility temperature for any given volume fraction and mean particle size is obtainable.

The fracture Charpy specimens were nickel plated, sectioned and the fracture surface examined with both optical and electron microscopy. It was seen that the size and depth of the dimples in the fibrous initiation stage of failure decreased as the mean particle size decreased. The variation of dimple size with yield strength, irrespective of carbide volume fraction, has been determined.

An attempt is being made to correlate the energy absorbed in forming a fracture with a given dimple size and depth with the fracture toughness or $K_{Ic}$ value for the material. The fracture toughness measurements are currently in progress.

## III. Strength and Fracture of Fiber Eutectic Composites
(with F. Darwish, Graduate Student)

The purpose of this investigation is to study the strength and fracture of unidirectionally solidified Aℓ-Ni eutectic alloy. Unidirectional solidification of this alloy results in the formation of $A\ell_3Ni$ fibers (hard and strong intermetallic compound) aligned parallel to the direction of growth and embedded in a continuous matrix that is mainly Aℓ with 0.04% Ni in solution.

Slow bend tests were carried out on Charpy bar specimens (fibers oriented parallel to the axis of the bar) and the load carrying capacity of the Charpy specimens was determined at different temperatures. This load dropped by a factor of two as the temperature was increased from $-196^{o}C$ up to $200^{o}C$. The variation was found to be linear. Some tests are to be carried out on specimens made out of the pure matrix (Aℓ - 0.04% Ni) and the results are to be compared with those obtained above. The comparison should lead to an explanation of the observed temperature dependence and whether it is due to change in fiber properties, matrix properties or both. A more detailed study has been carried out whereby the number of cracked fibers in the zone ahead of the notch (in Charpy bars) was determined as a function of the bend angle $\theta$. This number was found to increase as $\theta$ increased. A sharp increase that marked the onset of general yielding was observed at $\theta = 2^{o}$ (R.T. test) after which the rate of increase diminished considerably until eventually the specimen failed. More cracked fibers were found in the interior of the bar than on the surface of the same bend angle $\theta$.

Tensile tests showed dependence on temperature and strain rate for both the fracture stress and the tensile elongation; the former increased while the latter decreased as the temperature dropped.

Currently, the tensile and bending properties are being evaluated as a function of both temperature and strain rate for three different fiber orientations. More detailed experiments to determine number of cracked fibers as function of stress and strain are to be carried out on tensile specimens at different temperatures.

IV. A Theoretical Investigation of Dislocation Distributions in Two-Phase Systems (with David M. Barnett, Graduate Student)

The interactions between dispersed second-phase particles or inclusions and slip dislocations exert a large influence upon the strength and ductility of crystalline solids. An important example of such interactions may be represented by a planar array of slip dislocations which has been blocked by, and thus has piled up against, the second phase. The present study is an examination of the effects of second-phase size and rigidity upon the stresses associated with such blocked dislocation arrays.

Using the method of continuously distributed dislocations, exact analytical solutions are obtained for the stress fields associated with

1) a screw dislocation pileup at a rigid circular inclusion

2) a screw dislocation pileup at a semi-infinite second phase of finite rigidity

3) a screw dislocation pileup at a circular inclusion of finite rigidity.

The local stresses near the pileup tip are shown to be of the form

$$\tau_{ij} \sim \tau \sqrt{\frac{L}{4R}} \left(\frac{4R}{\rho}\right)^{g}, \qquad \frac{L}{R} > 2$$

$$\tau_{ij} \sim \tau \left(\frac{2L}{\rho}\right)^{g}, \qquad \frac{L}{R} < 2$$

where L is the slip line length, R is the radius of the second phase, $\rho$ is the radial distance from the pileup tip, and $\tau$ is the effective applied longitudinal shear stress. g, the strength of the pileup tip stress singularity, is a function of the elastic constants and is given by

$$0 < g = \frac{2}{\pi} \sin^{-1} \sqrt{\frac{G_1}{G_1 + G_2}} < 1 ,$$

where $G_2$ and $G_1$ are the second phase and matrix shear moduli, respectively. The physical significance of the above results is discussed in terms of image dislocation forces induced by the presence of a second phase ahead of a slip band.

An exact solution for the stresses generated by an infinite sequence of parallel screw dislocations piled up against an elastic half-plane of finite rigidity is also presented. The local stresses near the pileup tips are given by

$$\tau_{ij} \sim \left(\frac{2h}{\pi\rho}\right)^{g}, \qquad \frac{h}{L} < 2$$

$$\tau_{ij} \sim \tau \left(\frac{2L}{\rho}\right)^{g}, \qquad \frac{h}{L} > 5$$

where h is the separation distance between the slip bands. In addition, the more difficult plane strain problem involving an edge dislocation pileup against an elastic half-plane is formulated, and a method for determining the pileup tip stress singularity is discussed.

The results obtained from the above calculations are used to discuss relaxation of the pileup stresses by fracture initiation in the second phase and by cross-slip of the leading array dislocations around the second phase. Fracture initiation in a second phase which is harder than the matrix ($G_2 > G_1$) can only be predicted by an atomistic modification of the Griffith-Irwin-Stroh criterion used in single phase elasticity. It is shown that cross-slip should be the more favorable relaxation mode when $L/R > 2$, and that fracture initiation should be possible only when $L/R < 2$. In typical two-phase systems this analysis predicts that fracture initiation in the second phase should be possible only when the inclusion diameter is greater than about one micron.

## V. Elastic-Plastic Cracks in Two-Phase Materials
(with Tsu-Wei Chou, Graduate Student)

A theoretical approach has been used to investigate the behavior of the elastic-plastic crack in a two-phase system. It is intended that the result will be extended to determine the crack propagation behavior in fiber composites.

In one of the approaches to this problem, we adopt the shear crack model, originally suggested by Bilby, Cottrell and Swinden. The calculation of plastic regions as a function of crack position has been made for a material with a rigid second phase, with both the crack and the plastic region in the soft phase. The result will next be extended to two-phase systems of finite rigidity.

Besides using the dislocation model approach for a crack, an alternative method has been used based upon classical continuum elasticity. Crack problems in materials containing rigid surface films and fiber composites are currently being studied.